Features of the gas dynamics and local heat transfer in intake system of piston engine with supercharging

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Abstract. Comparison of experimental research results of gas dynamics and instantaneous local heat transfer in the intake pipes for piston internal combustion engines (ICE) without and with supercharging are presented in the article. Studies were conducted on full-scale experimental setups in terms of gas dynamic nonstationarity, which is characteristic of piston engines. It has been established that the turbocharger installation in a gas-air system of piston internal combustion engine leads to significant differences in the patterns of change in gas-dynamic and heat transfer characteristics of flows. These data can be used in a modernization of piston engines due to installation of a turbocharger or in a development of gas-air systems for piston ICE with supercharging.

1. Introduction

One of the major trends of development of modern internal combustion engines (ICE) is to increase their power and economical efficiency. A possible solution of this problem is to install the turbocharger (TC) on a piston engine. Usually the turbocharger installation is viewed solely as an effective way of increasing the mass airflow through an engine cylinders and a method of improvement of its technical and economic indicators [1-4]. The question about the influence of TC on gas dynamic and heat transfer characteristics of flow in a gas-air systems of piston engine is hardly considered in the literature. However, it is clear that the installation of TC will lead to a significant change in the thermal and mechanic characteristics of the gas flow in a gas-air system. For example, some studies of the effect of a turbine in the exhaust pipe on gas dynamic and heat transfer characteristics of pulsating flows were carried out earlier [5, 6]. It has been established that maximum speed of air flow in the exhaust pipe with the turbocharger was lower than in the pipe without TC (the differences reach 40 %). The presence of the turbocharger in exhaust system leads to some smoothing of fluctuations of the flow velocity during the whole working cycle of piston ICE. Also, it has been determined that decreasing the intensity of heat transfer was observed in the exhaust system with the turbocharger, it was characteristic of all rotation frequencies of TC and piston ICE. The decrease in a heat transfer intensity in the exhaust system with TC was 10-15 % at an excess pressure of p_b = 1,0 bar and 15-20 % at an excess pressure of p_b = 2,0 bar. Reduction in a heat transfer intensity to the walls of the exhaust pipe in engines with TC should positively affect the working process and the technical and economic parameters of the piston ICE. Because greater amount of heat will work in a turbocharger, and not to be lost through walls of the exhaust pipe in this case.

Comparison of results of experimental research of gas dynamics and instantaneous local heat transfer in the intake pipes for piston internal combustion engines without and with supercharging are presented in this article. The studies were carried out taking into account a gas-dynamic nonstationarity.

2. Experimental setups and measurement equipments

Experimental setups for experimental studies of gas dynamics and local heat transfer in the intake systems have been designed and manufactured. They are full-scale models of single-cylinder engine with dimensions of 8.2/7.1 (piston diameter – 82 mm stroke – 71 mm) with or without turbocharger (Figure 1). The prototype for the created models was a car engine of the Russian VAZ company. The drive of a crankshaft was carried out using an electric motor. The frequency of crankshaft rotation was varied in the range from 600 to 3000 rpm. The turbo was carried out by means of the turbocharger TKR-6. Frequency of TC rotor rotation was changed in the range from 35 000 to 46 000 rpm. A detailed description of experimental setups is presented in [7].

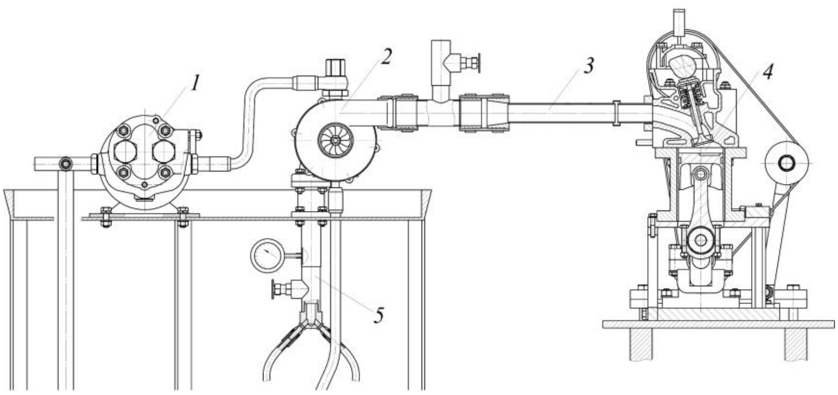

Figure 1. Scheme of the experimental setup: *1* – oil pump; *2* – turbocharger; *3* – intake pipe; *4* – piston engine; *5* – compressed air supply system.

Automated system of collecting and processing experimental data was created for the research. Instantaneous values of air flow velocity w_x and local heat transfer coefficient α_x was determined using the thermal anemometer of the constant temperature. The applicability of hot-wire method for studying gas exchange processes in piston engines is illustrated in the following works [1, 2]. In this work, the sensitive element of the anemometer sensor was nichrome thread which had a diameter of 5 μm and length 5 mm. A sensor with a free thread was used to measure the air flow velocity. The thread was placed perpendicular to the axis of the investigated pipe. The local heat transfer coefficient was determined using the thread, which was placed on the fluoropolymer substrate. The fluoroplastic substrate was mounted flush with the wall of the pipe. Measurements of the frequency of crankshaft rotation and the rotor of the turbocharger was carried out by means of tachometers. The WIKA pressure sensor was used to determine the instantaneous values of the static flow pressure in the pipes.

Traditional straight duct with round cross section was chosen as the starting base for research. This choice is explained by a small number of experimental data on gas-dynamic and heat transfer characteristics of flows in gas-air systems of the piston ICE and a weak knowledge of this subject in the literature. The length of intake pipe was 300 mm. Inner diameter of the intake pipe was 32 mm.

3. Local heat transfer determination method

Thermal anemometry method to study a gas-dynamics and local heat transfer in gas flows were chosen on the basis of literature analysis [8, 9]. It is known that the small dimensions of sensing element of the thermo-anemometer sensor do not introduce significant changes in a nature of gas flow; high sensitivity allows one to record the fluctuations of a variables with small amplitudes and large frequencies;

simplicity of a hardware scheme gives the opportunity to securely record an electrical signal from the output of the thermal anemometer for storage and further processing on a personal computer. It should be noted that high speed of the thread sensors was a key factor in its selection because other types of sensors does not provide the necessary time resolution.

As noted above, the thermal anemometer of constant temperature was used to determine a local heat transfer coefficient α_x. The sensitive element of the thermo-anemometer sensors was a nichrome filament with a diameter of 5 μm and a length of 5 mm. This thread was installed on a fluoroplastic substrate, whose surface was mounted flush with the wall of the pipeline. It should be noted that the filament diameter was less than the average microroughness of the substrate.

Preliminary design evaluation and pilot experiment have shown that it was not possible to provide the implementation of the known techniques for a direct determination of a local heat transfer coefficient using wire sensors in this case. Therefore, in this study the determination of a local heat transfer coefficient was based on indirect calibration based on known empirical relationships, i.e. by the method proposed by S.S. Kutateladze. It is based on the basic indicator of a local heat transfer of a well-studied process. For this case, stationary heat transfer was chosen in a long straight pipe (l / $d \geq 50$) with a circular cross section. The calibration was to relate a calculated heat transfer coefficient α (W/(m^2·K)) for a long straight pipe and a signal value from the thermo-anemometer sensor U (V).

Thus, in this paper the determination of a local heat transfer in a pulsating flow of gases is based on the idea of hydrodynamic analogy of heat transfer (Reynolds analogy). It is based on the assumption of the unity of a transfer processes of momentum and heat in turbulent flow and establishes the quantitative relationship between heat transfer and hydraulic resistance (Stanton criterion).

4. Features of the gas dynamics and local heat transfer in the intake system of the piston engine with supercharging

It has been established that there are significant differences in the patterns of change of air flow rate in piston engines with supercharging and without it. A sharp and rapid increase of the air flow velocity in the intake pipe is observed immediately after the valve opening in an engine with a turbocharger (Figure 2). This is due to the fact that the pressure in the intake pipe is above atmospheric pressure and exceeds the pressure in the engine cylinder at the end of the exhaust.

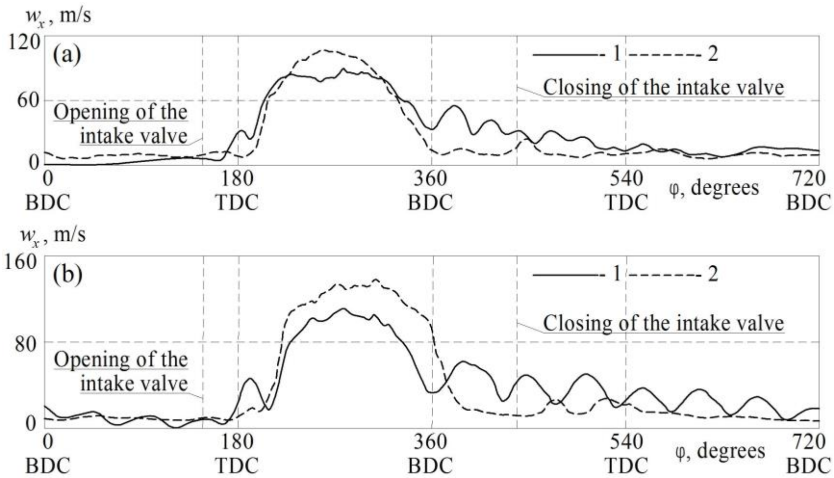

Figure 2. Local (l_x = 140 mm) flow velocity w_x in intake pipe as a function of crankshaft rotation angle φ of piston ICE with (n_{TC}= 35000 rpm) and without turbocharger for the crankshaft rotation speed: (a) n = 1500 rpm; (b) n = 3000 rpm. System configuration: (1) without and (2) with turbocharger.

It has been established that maximum values of air flow rate w_x in the intake pipe in the engine with a supercharger are 15-25 % higher than in the engine without the TC (Figure 2). It has been established that the differences in maximum values of air flow velocity are increased with increasing rotation frequency of the turbocharger rotor. The differences reach 40 % at n_{TC} = 45000 rpm.

It should be noted that the air flow velocity in the intake pipe is not equal to zero after closing the intake valve. Pulsations of the flow velocity with a fairly high amplitude are observed in the pipe. This phenomenon is typical for the intake systems of piston engines with supercharging and without it. See also article [10].

Similar effects are recorded in the graphs of change of the flow pressure in the intake system (Figure 3). Fluctuations in the flow pressure p_x in the intake pipe after closing the valve are observed. The fluctuations are most characteristic of the engine without the TC. Small fluctuations in flow pressure during the entire work cycle are observed in the intake pipe of the engine with supercharging. These fluctuations are the result of the work of the turbocharger blade apparatus [11].

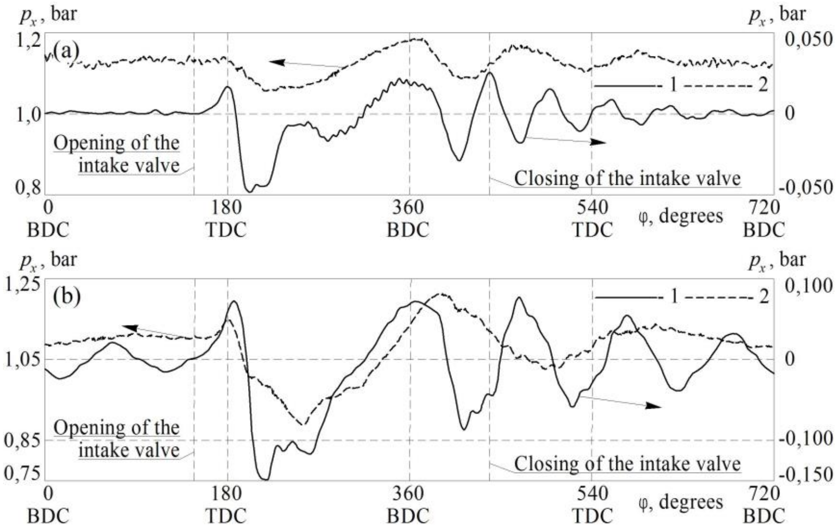

Figure 3. Local (l_x = 140 mm) flow pressure p_x in intake pipe as a function of crankshaft rotation angle φ of piston ICE with (n_{TC}= 35000 rpm) and without turbocharger for the crankshaft rotation speed: (a) n = 1500 rpm; (b) n = 3000 rpm. System configuration: (1) without and (2) with turbocharger.

The maximum and average values of α_x in the intake pipe of a piston internal combustion engine with a turbocharger is significantly increased, compared with values for the engine without TC (Figure 4). This is true for all frequencies of the crankshaft rotation and the turbocharger rotor. For example, the maximum values of local heat transfer coefficient in the intake pipe of the piston ICE with a turbocharger are almost 2 times higher (at engine speed of 600 rpm) compared to α_x in internal combustion engines without TC. The difference is about 75% at n = 3000 rpm. The increase of the local heat transfer coefficient in the intake pipe in the presence of TC can lead to the following:

- heating air from the hot walls of the pipe during the intake process;
- increasing thermal stresses in the parts and components of intake system.

It is shown that the pulsations of the local heat transfer coefficient in the intake pipe of the internal combustion engine with supercharging are observed on all modes of operation. Pulsations of α_x have a large amplitude in the case of installation of the turbocharger than the engine without it. The fluctuations intensity of the local heat transfer coefficient is decreased with increasing rotor speed of the turbocharger n_{TC}. The fluctuations intensity of the α_x is increased with increasing speed of the crankshaft n.

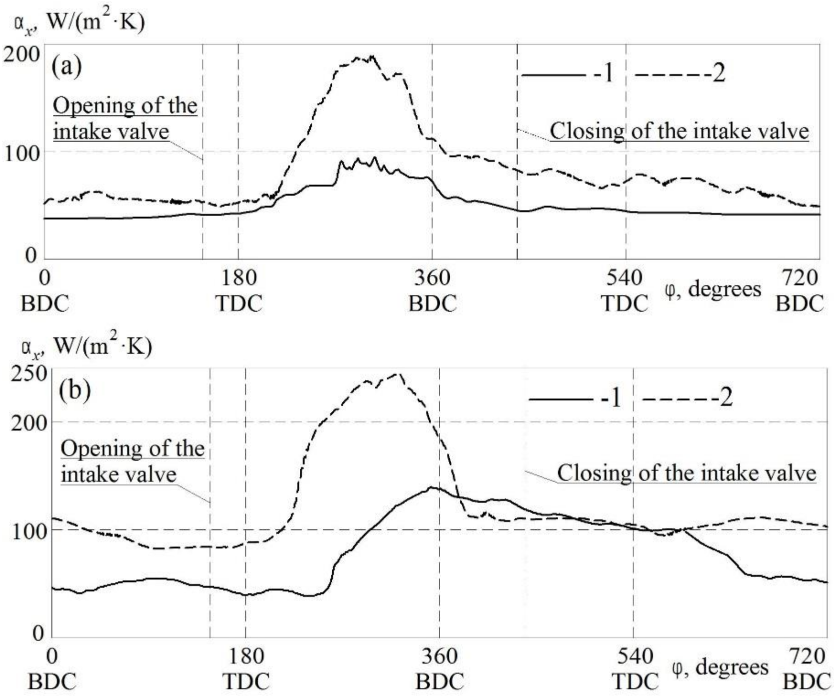

Figure 4. Local (l_x = 150 mm) heat exchange coefficient α_x in intake pipe as a function of crankshaft rotation angle φ of piston ICE with (n_{TC}= 35000 rpm) and without turbocharger for the crankshaft rotation speed: (a) n = 1500 rpm; (b) n = 3000 rpm. System configuration: (1) without and (2) with turbocharger.

Data about the instantaneous local heat transfer in a gas-air systems of piston internal combustion engines with supercharging are necessary for:

- calculations of heating air in the intake process;
- to determine the dynamics of the temperature distribution in the parts and components of intake system;
- calculations of thermal stresses.

5. Conclusions

The main findings of the research are as follows:

1. It has been established that the turbocharger installation in the intake system of a piston internal combustion engine leads to significant differences in the patterns of change in gas-dynamic flow characteristics. Maximum values of air flow velocity in the intake pipe in the engine with a supercharger are 15-50 % higher than in the non-turbo engine; these differences are increased with an increase of the rotor speed of turbocharger;
2. Maximum values of heat transfer coefficient in the intake pipe of a piston engine with a supercharger are increased up to 2 times. The average values of a local heat transfer coefficient in the intake pipe of a piston ICE with supercharging are increased by up to 45 % compared to engines without turbocharger.
3. The obtained data can be used to design intake and exhaust systems when upgrading the existing engine or designing a new internal combustion engine with supercharging.

Acknowledgments

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